Building safely by design

Using digital design models to improve planning for safe construction

Report submitted to the IOSH Research Committee

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The work on which this report is based was conducted in the Design Innovation Research Centre at the University of Reading. It was initiated following the death of a professional acquaintance at work on a construction site.

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Abstract

The aim of this project was to identify effective modes of interaction between designers, construction design and management (CDM) co-ordinators and builders, in which they collaborate – with the aid of a virtual reality (VR) tool as a catalyst for their conversation – to design safe construction processes. The objectives were to develop a method for assessing the safety implications of a detailed design model of a building; develop immersive and augmented visualisation techniques for use in this assessment; and trial the process with construction workers on a construction project.

At the University of Reading, a digital laboratory was set up, and strategies were developed for visualising models and recording collaborations. Interactions with experienced industrial partners informed the research design – this evolved from the original plan. Experiments were conducted with both industry partners and graduate students.

Using the immersive environment, experienced safety professionals discussed hazards relating to a crane, a roof, edge protection, voids, stairs, scaffolding and cladding. Through interaction with the model, these professionals were able to understand the constraints of the building and the site. They drew attention to a broader set of alternative construction methods than graduate students.

The experiments highlight the practical challenges of building safely by design, as well as the potential of visualisation using 3D stereo displays. The experiments also suggest that rich models are needed which direct attention to relevant aspects and allow professionals to probe and discover further contextual information about the project, and to see it within the context of the site.

As building information modelling (BIM) becomes widely used in construction, it raises new opportunities and questions about how digital models can be used to build safely by design. This study suggests a new trajectory of research on digital tools that fosters mindful practices, and the rich interactions associated with these practices. Further research is underway to extend this study and address some of its limitations.

Executive summary

Objectives

The increasing use of building information modelling (BIM) in construction raises questions about how digital models can be used to build safely by design. The objectives of the study were to:

- develop a method for assessing the safety implications of a detailed design model of a building
- develop immersive and augmented visualisation techniques for use in this assessment
- trial the process with designers and construction workers on a construction project.

Prior research and approach

'Building safely by design' is an important feature of the UK's Construction (Design and Management) (CDM) Regulations. Digital tools have been developed for construction safety, but less attention has been paid to digital tools that support safety by design. We undertook a critical reading of the research literature on construction safety and design to inform tool development. This indicated that the link between safety and design is more subtle and problematic than earlier studies suggest.

Methods

Our approach was to bring designers and builders together to promote active discussion and engagement with safety issues. This approach was informed by studies of organisational practices that highlight the role of 'mindful' action in sustaining and developing safe construction practices.

A digital laboratory set up at the University of Reading provided different ways to view models using desktop and immersive displays, the ability to view these models through 3D stereo displays, and to record collaborations using them. Experiments were conducted with both industry partners and graduate students. The empirical work included:

- 11 visits to and from industrial collaborators
- two recorded sessions with industrial partners, who, having completed an initial assessment, viewed a model in the CAVE in order to assess the safety implications of a detailed design
- 47 individual assessments by graduate students, followed by 10 pairs of students viewing a model collaboratively to assess the safety implications of a detailed design.

Interactions with industrial partners informed the research design – which evolved from the original plan – both to address the practical challenge of getting designers, CDM co-ordinators and builders together, as well as to see the project as a pilot for later work with the project design model and safety data for a specific construction project.

Findings

The interactions with safety professionals highlighted the many practical challenges of building safely by design, as well as the use of models to facilitate conversations between builders and designers. Using the immersive environment, the experienced safety professionals discussed hazards relating to a crane, a roof, edge protection, voids, stairs, scaffolding and cladding. In addition, they appreciated the potential of stereo viewing of 3D models to facilitate safety discussion. They articulated a broader set of methods for dealing with hazards than graduate students. In particular, their solutions drew on knowledge from the construction site and introduced new equipment and processes that were not modelled. For example, they identified that using prefabricated building components would reduce or eliminate the hazards to workers that would be posed by working at height to form and pour cast-in-place concrete components. Graduate students were poor at developing such solutions that drew on knowledge outside of the model.

Conclusions

The experiments suggest that:

- the relationship between safety and design is complex – in visualising and using models, this relationship needs to be investigated further in order to develop an evidence base that shows how conversations around design models can improve building safely
- the content of models used by designers to review safety needs to be established in detail. Rich models are needed that direct attention to relevant aspects, as well as to allow professionals to probe and discover further contextual information about the project, and to see it within the context of the site and the construction process

- work is needed on the models used to teach safety issues on construction sites. An option here would be for the research team to model a wider set of alternatives for permanent and temporary works, and for prefabrication and building to be carried out on site.

This project suggests a new trajectory of research on digital tools that fosters mindful practices, and the rich interactions associated with these practices. Further research is underway to extend this research and address some of its limitations. There are also directions suggested for work on the pedagogical methods that use models in teaching students about safety issues on construction sites.

Glossary

Acronym	Term	Definition
4D CAD	four-dimensional computer-aided design	Models that show the three spatial dimensions of a building's geometry, together with the ways in which they change over time, eg as a building is constructed
BIM	building information modelling	The process of developing information-rich object-oriented models. The term is sometimes used to denote the models themselves
CAVE	CAVE	A recursive acronym, CAVE Automatic Virtual Environment, which indicates an immersive 3D virtual reality system
CDM	construction (design and management)	This term is most commonly used in relation to the UK Construction (Design and Management) Regulations. Under the Regulations, CDM co-ordinators have particular duties to assist clients in meeting their responsibilities, while designers are required to minimise the hazards associated with construction at as early a stage as possible
CHASTE	construction hazard assessment with spatial and temporal exposure	A system for analysing construction hazards for different trades, taking into account both changes to the physical environment and activities performed throughout the construction process
CHAIR	construction hazard assessment implication review	A process for evaluating the construction, maintenance, repair and demolition safety issues associated with design
CIGJS	computer image generation for job simulation	An approach to occupational risk analysis developed to support job safety analysis. It simulates the actual work situation using computer image generation and makes the use of JSA possible at the design stage
CJSA	construction job safety analysis	Job safety analysis was developed for safety risk assessments for industrial manufacturing. Unlike manufacturing, construction sites are constantly changing. To address this situation, this structured method of hazard analysis was developed for construction sites
CSA	critical space–time analysis	A method that associates certain visual features of workspace planning with the workspace competition between different construction activities. It deals particularly with analysing this space–time competition that occurs between activities
DFSP	design for safety process	Applied virtual reality and database technologies that assist users in identifying potential construction risks inherent in a design at the construction stage

FACE	Fatality Assessment Control and Evaluation	US programme that provides approximately 500 descriptions of construction industry fatalities, including a detailed incident narrative and recommendations
GIS	geographic information system	A computer system that stores, manipulates, combines and visualises geographic data
HAZOP	hazard and operability study	A structured qualitative approach to the examination and evaluation of potential risks to personnel or equipment
HSE	Health and Safety Executive	UK government body that seeks to protect people from risks to health or safety arising out of work activities
IFC	Industry Foundation Classes	A standard format for representing building components in an open-source language, developed by an international organisation, buildingSMART
IOSH	Institution of Occupational Safety and Health	The world's largest membership body for health and safety professionals
MEP	mechanical, electrical and plumbing	The services put into a building
NIOSH	National Institute for Occupational Safety and Health	Government institute responsible for occupational safety and health in the USA
PECASO	patterns execution and critical analysis of site-space organisation	A computer-based tool developed to encapsulate and evaluate the outcome of a critical space–time analysis
RIBA	Royal Institute of British Architects	UK professional institution and membership organisation for the architectural profession, which produces a plan of work for building design
SABIC	safety analysis of building in construction	A system that applies 4D building information modelling to the analysis of structural safety during construction processes
ToolSHeD	Tool for Safety and Health in Design	A web-based design decision tool that provides decision support for the assessment of the risk of falling from a roof during building maintenance work
VCL	virtual construction laboratory	A knowledge-based virtual reality system developed to enable the planner to conduct virtual experiments on innovative construction technologies and processes
VRML	Virtual Reality Modelling Language	A file format for saving 3D geometries and behaviours, which is itself readable and editable as text

1 Introduction

The design of the built environment has a major impact on individuals' quality of life. In the same way that society has a responsibility to ensure that material resources are carefully used, we share a responsibility for the safety of those who build the buildings and infrastructure that we inhabit. Construction of the built environment may, at times, still involve sweat, but it should not involve blood and tears. Yet, safety is a major issue across global construction industries. There were 9.7 fatalities reported per 100,000 construction workers in Europe in 2006[3] and 11 per 100,000 in the USA in 2007.[4] In the UK, accident rates in construction are roughly double those for manufacturing, with 53 construction workers dying in 2008/09 and thousands more sustaining major injuries at work.[5] Over the long run, safety has been improving in many countries,[6] but any loss of life[7] and injury through construction accidents is unacceptable.

The physical task of putting together buildings and infrastructure remains a locally embedded physical activity, but it has also been changed by the digital economy, which brings with it new 'splintered yet connected' ways of working across global networks of design services and product supply.[8,9]

The report describes research conducted through the Institution of Occupational Safety and Health (IOSH). IOSH funded one year of researcher time – between March 2010 and February 2012 – to explore the use of digital design models to improve planning for safe delivery.

The rest of this introduction describes the background to the problem, as well as the project's aims, objectives, approach, methods and rationale. The paper proceeds with an overview of the literature. Section 3 describes the study design and methods for the experimental work. Section 4 reports on the findings, and the final section discusses the findings and outlines the direction of future research.

Background to the problem

The immediate causes of accidents in construction are well documented. They include falls from height; being struck by a moving vehicle; being struck by a moving/falling object; or becoming trapped by something overturning/collapsing.[10] While there are significant challenges in collating accurate accident statistics and comparing such statistics internationally, Table 1 indicates the kinds of incident that occur.

Errors in complex and hazardous environments have often been regarded in the literature as either the failure of individuals, where individual carelessness led to the accidents, or the failure of complex organisations,[11] where a wider set of organisational structures and practices led to individuals being put into unsafe situations. There is, however, a growing recognition that accidents are often the result of multiple interacting factors.[12]

On the construction site, the design of the permanent structure is one of those factors that may interact to cause an accident. The UK's Construction (Design and Management) (CDM) Regulations 2007[13] require designers to minimise the hazards associated with construction at as early a stage as possible. The involvement of construction safety experts early in design could improve designs directly, as well as improve designers' awareness and knowledge. Safety could be enhanced through collaboration between designers, CDM co-ordinators and builders early, during the design phase. However, research has identified challenges in transferring knowledge of this kind from the site back to the design office. Collaboration between designers and builders in general, and attempts to improve safety performance in particular, are impeded by a clash between forms of knowing: through written reports and documentation, which is dominant in the professions; and through experiential learning, which is dominant in the trades.[14–17] However, despite the requirements of the CDM Regulations in 1994 and 2007, designers are still failing to adequately anticipate health and safety issues in construction.

Research aim and objectives

The aim of this project was to identify effective modes of interaction between designers, CDM co-ordinators and builders in the design of safe construction processes, with a virtual reality (VR) tool as a catalyst for their conversation. The objectives, which were set out in the stage 1 proposal, were to:

- develop a method for assessing the safety implications of a detailed design model of a building
- develop immersive and augmented visualisation techniques for use in this assessment
- trial the process with designers and construction workers on a construction project.

Table 1 Injuries to employees by kind of accident, injury severity and nation

Source: Perlman, Sacks & Barak[2]

	UK (2009)			USA (2008)		Israel (2007)		South Africa (2007)	
Kind of accident	Fatal	Non-fatal major	Over-three-day	Fatal	Non-fatal major	All non-fatal (incidents)	All non-fatal (total absence)	Fatal	Non-fatal
Contact with moving machinery	2	134	270	–	–	317	14,165	–	–
Struck by a moving/flying/falling object	3	529	1,035	115	22,230	471	21,431	10	4,474
Struck by a moving vehicle	4	68	64	119	3,090	740	31,080	28	857
Strike against something fixed or stationary	2	101	274	–	8,410	681	25,469	0	975
Injured while handling, lifting or carrying	–	434	2,462	–	11,100	435	19,836	–	–
Injured while using hand tools	–	–	–	–	–	719	23,781	–	–
Slips, trips or falls on same level	1	780	1,407	–	11,520	806	41,930	0	683
Falls from a height:	9	989	755	266	13,970	966	57,794	11	1,922
• up to and including 2 metres	–	560	498	–	–	–	–	1	516
• over 2 metres	9	266	115	–	–	–	–	10	1,406
• height not stated	–	163	142	–	–	–	–	–	–
Trapped by something collapsing/overturning	3	27	22	–	–	72	3,161	4	877
Drowning or asphyxiation	2	–	1	–	–	–	–	–	–
Exposure to, or contact with, a harmful substance	–	43	144	106	4,210	82	2,708	4	199
Exposure to fire	–	13	17	7	400	18	452	0	92
Exposure to an explosion	1	10	4	–	–	14	476	–	–

Contact with electricity or electrical discharge	–	34	66	–	–	22	944	0	36
Injured by an animal	–	5	18	–	130	11	234	–	–
Acts of violence	–	11	18	36	90	19	1,058	–	–
Other kinds of accident	–	97	219	–	–	451	18,119	3	95
Injuries not classified by kind	6	11	13	–	–	–	–	0	21
Totals	33	3,286	6,789	649	75,150	5,824	–	71	12,153

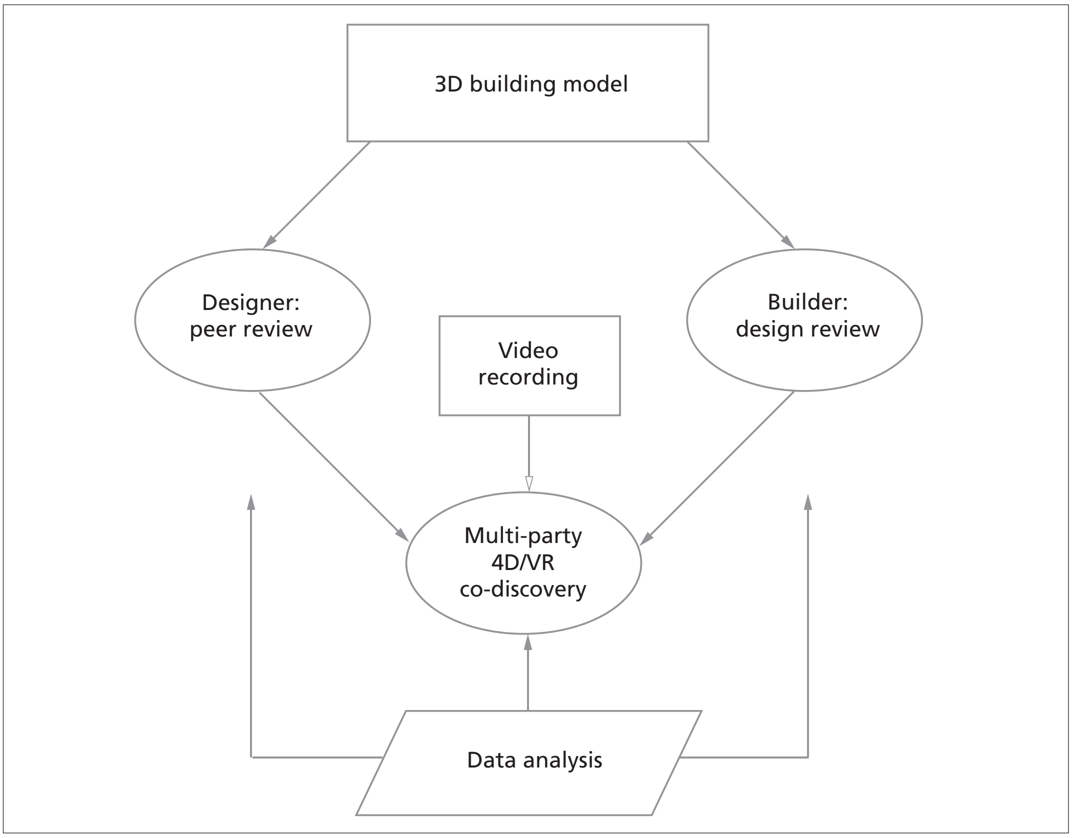
The colour scheme shows values that are high (red), medium (white) and low (green) relative to the other values in the same column.

The power of visual images in enabling designers to appreciate the safety issues has previously been recognised in the DVD series ‘Safeguarding people: achieving design excellence’.[18] The design for safety process (DFSP) tool, developed on a standard desktop computer,[19] demonstrates a simple process visualisation of construction for the assessment of safety hazards by designers. Research by Sacks, Rozenfeld & Rosenfeld[20] identified the most common loss-of-control scenarios for a range of construction activities and showed how they could be used in concert with BIM models to identify exposures of workers to hazards over time. However, numerical analysis of the type implemented in CHASTE provides no indication of the characteristics of the design that generate hazards, nor can it suggest safer design alternatives. Visualisation can be used to engage designers and builders at an experiential level, empowering them to identify emergent safety issues, as well as to automate the identification and display of such issues from databases.

Approach and research design

The research is experimental, visualising design through immersive VR (a CAVE) and using desktop software as a laboratory in which ‘design of safe process’ meetings and conversations can be conducted and monitored. The data collected (using video and audio recordings, as well as researchers’ notes) have been analysed to understand the kinds of interaction that support learning about construction safety. The experiment was designed as a safety assessment, and was carried out in two stages, as outlined in Figure 1. In the first stage, participants were asked to make separate individual assessments of construction risks and hazards through observation of a 3D building model that had a variety of design pitfalls impacting on construction safety. During the assessment, participants were able to navigate and manipulate the model. In the second stage, two experienced safety professionals reviewed and discussed the same project design model and its safety implications. As designers, CDM co-ordinators and builders bring knowledge and expertise from different domains, the collaboration indicated in Figure 1 used the 4D/VR environment as a catalyst for inter-disciplinary collaboration.[21] A video recording system was used to capture the dialogue for post-experimental analysis. The original intention was to analyse whether participants identified design pitfalls in the collaboration that they had failed to identify in the individual assessments; and whether there were risks identified individually that were not discussed in the collaboration. One of the greatest strengths of video-based research methods is that video provides a data source which can be re-visited and re-scrutinised, providing the opportunity to share, discuss and collaboratively analyse with colleagues and continually return to the data with new analytic lines of inquiry.

Figure 1 Experimental procedure



Rationale and significance

This research investigated the use of digital visualisation to address three problems that hamper ‘design for safety’ in construction. First is the failure to consider safety in design – the scope for design change to enhance safety declines as design progresses. Accordingly, safety should be considered as early as possible in the construction process. The second is the lack of skills to do this effectively – design for safety encompasses not only design of the built product (the focus of designers) but also design of the building process (the focus of builders). For designers to design effectively for safety, they need to bring construction process design skills to bear. A good way to do this is to engage with builders in ‘design-assist for safety’ roles. The third is the challenge of collaboration – builders and designers have different modes of ‘knowing’ (experiential versus documentary), which impedes the exchange of knowledge between them.

2 Literature review

After outlining the practices of construction safety through design, two strands of research are reviewed. The first develops digital tools to visualise and address issues of construction safety. In particular, this review highlights studies that have used VR and four-dimensional computer-aided design (4D CAD), and finds more generally that, within this strand of research, while various digital tools have been developed by researchers for use in the construction phase, few have been developed to support design for construction safety. The second strand of literature draws on theories of organisation to understanding safety-critical, digital and design practices. This literature raises a concern about 'mindlessness' in the use of technologies, which has implications for research in the first strand. The review highlights the need for further work to explore the relationships between construction safety and digital design practices. Bringing these strands together suggests new kinds of interventions, promoting mindfulness through multi-party collaboration on safety around digital models.

Construction safety through design

According to Szymberski,[22] construction safety should be a prime consideration in the conceptual and preliminary design phases. His hypothetical time/safety influence curve illustrates the idea that the ability to influence construction site safety is progressively lost as the project moves into the construction phase, with a significant opportunity in design. Until the implementation of recent legislation in the UK, France and Australia, however, designers' consideration of construction safety has been largely voluntary.[23] In the USA, construction contracts and regulatory requirements from the Occupational Safety and Health Administration (OSHA) clearly place the burdens for worker safety solely on the constructor.[24] This approach is still widespread across many countries, but has been changing since more parties have been brought into litigation regarding workers' injuries. A recent study of the effect of European Directives on construction workplace accidents shows a statistical decrease in incidents since legislation came into force.[25] Project owners have also become more concerned about safety performance on their projects.[23] Recent research indicates that:[26]

> … many designers still think that safety is 'nothing to do with me' although there are a small cohort who want to engage and are having difficulty doing this because they do not fully understand what good practice looks like.

The CDM Regulations require consideration to be given to health and safety in the planning and design of construction work in the UK. Thus, the contractor is no longer left with the sole responsibility for safety during construction. The aim of the CDM Regulations is to bring about a culture change in the construction industry by requiring all those involved in the development and construction process to consider health and safety issues. Baxendale & Jones[27] argue that the philosophy behind this is to establish a team that will have the competence and resources to manage the project without undue risk to health and safety. Since the release of the CDM Regulations in 2007, the appointment of a planning supervisor, namely the CDM co-ordinator, has been central to a client's responsibilities. The CDM co-ordinator should be appointed as early as possible to allow adequate time to address issues during the planning and design stage, including the preparation of the pre-tender stage health and safety plan.[26] The Regulations also recognise other parties – including the client, designer, principal contractor and subcontractors – as having responsibilities for health and safety management on a construction project, and highlight the importance of multi-party collaboration for safe construction. The level of awareness of the distinctive duties and how well these are co-ordinated during the various phases of the construction project underpins health and safety.[28] Researchers have become involved in developing short courses for construction professionals, adopting an integrated problem-based and collaborative learning approach, to help professionals understand CDM roles and duties.[29]

An early CDM implementation study[27] suggests designers need to indicate a knowledge and understanding of how risks and hazards to health and safety can arise in construction, and how they can be avoided or reduced through design. Some designers, especially those in design-build firms, are able to address construction worker safety in their designs.[23] These designers work with in-house colleagues who are responsible for the construction of the project. By working together in the same firm, they begin to appreciate each other's concerns. Good ideas will be remembered and used on subsequent projects. Nevertheless, many designers who are not part of design-build firms note that they lack the skills and training to address construction worker safety. This highlights the need for a central body of knowledge available for designers to address safety in their designs. To address this, Gambatese, Hinze & Haas[30] accumulated over 400 design suggestions for construction safety through a literature search, interviews with construction industry personnel, worker safety manuals, safety design manuals and checklists. These design suggestions were compiled in the 'Design for Construction Safety Toolbox'.[30]

The relationship between construction fatalities and design has been investigated by Behm.[24] This research was rooted in the US NIOSH Fatality Assessment Control and Evaluation (FACE) programme, which provides approximately 500 construction industry fatality descriptions, including a detailed incident narrative and recommendations.[31] It used statistical hypothesis testing to examine 224 fatality investigation reports, and the results suggested that 42 per cent of the fatalities reviewed were linked to design issues. This implies that the associated risk that contributed to the incident could have been reduced or eliminated had construction safety been considered in design. The research established a link between construction fatalities and design for construction safety.

Gambatese, Behm & Rajendran[32] and Behm[24] provide retrospective evidence that design has an impact on construction site safety. Fatalities that occurred during the construction of thermal and moisture protection, doors and windows (including skylights), and metal design elements, were more often related to design issues. This finding was largely due to:[32]

> … the prevention of falls when erecting structural steel framing and while building and maintaining roofs where permanent anchor points, lifeline systems, and other forms of permanent fall protection could be designed into the permanent features of the structure.

The authors argued that 'roofing and structural steel constructors would benefit mostly from the implementation of the design for safety concept'.[32] This finding indicates that design for safety suggestions and modifications may have a positive impact on fall prevention and protection measures. As identified earlier, these are a major cause of fatalities in construction.

The construction hazard assessment implication review (CHAIR) method provides a process for evaluating construction, maintenance, repair, and demolition safety issues associated with design.[33] It is based on hazard and operability studies (HAZOPs)[34] and consists of a three-stage review by multidisciplinary teams, involving all stakeholders in the design, construction and use of a facility. The first review occurs at the conceptual design phase. At this stage, the design is divided into logical components and, for each component, sources of OSH risk are identified and assessed. Taking place after the detailed design has been completed and immediately prior to construction, the second review focuses on OSH issues arising in the construction and demolition phases of the project, while the third review focuses on maintenance and repair of the facility. Trialled by several projects, this is an innovative adaptation of the HAZOP studies method to construction.

To improve construction safety, Atkinson & Westall[6] identify a number of practical actions that designers can take, including:

- asking the contractor how work will be constructed
- finding out component sizes for safe installation
- co-ordinating the programme for the safe sequencing of work
- ensuring the contractor has an in-depth understanding of the design rationale.

However, the prevalence of traditional design-bid-build contracting arrangements and the resulting complex hierarchy of subcontracting on any modern building create a significant organisational distance between designers in any domain and the relevant subcontractors who will actually perform the work. In the USA, for example, there is still significant reluctance on the part of designers to take an active role in addressing construction safety due to liability concerns when dictating means and methods.[30] There are significant challenges in implementing these actions, even in new forms of procurement where designers and contractors do work more closely together, and concerns that changes in design are often only implemented as attempts to protect the designer from liability rather than to effect any real change in design to support safety.[35] There is a dearth of research and practical experience in incorporating safety considerations into the early stages of design.

Design for construction safety requires collaboration between the designer, owner, constructor, and other project parties,[32] and such multi-party collaboration is emphasised in the CDM Regulations. Yet, Gambatese *et al.*[32] note that it is incorrect to assume that a focus on design for safety will automatically eliminate construction site fatalities. It is one element within a more holistic approach to minimising construction project risk and enhancing worker safety, through multi-level risk assessment and hazard prevention mechanisms throughout the delivery of a building project. There is more work to be done to establish a robust evidence base to show the aspects of construction safety where design has the largest role to play. Yet the work discussed here indicates that the quality and nature of design does have some impact on construction safety. Hence, in the next section, we begin the review of the first strand of literature by considering the use of digital tools for managing safety through the construction phase, and then continue in the following section by considering the use of tools in the design phase.

Tools for visualising design and construction to improve safety

Researchers have developed a range of new tools for use in the construction phase to help contractors achieve safety in their projects. These combine the use of online databases, VR, geographic information systems (GISs), 4D modelling and sensing/warning technologies for site hazard prevention and safe project delivery. As shown in Table 2, many of these focus attention on product, process and operation in construction safety management.

Table 2 Selected construction safety systems and projects that apply digital technologies

Tool/Project and citation	Approach	Focus	Technology
Health and safety competence assessment[36]	Assessment of duty-holders' competence	Project	Online databases
Construction safety and health monitoring system[37]	Monitor project performance	Project	Online databases
Computer image generation for job simulation[38]	Simulation for job safety analysis	Operation	VR
Design for safety process[19,39]	Simulation and review of construction process for design-related safety issues	Process and product	VR
Virtual construction laboratory[40]	Simulation and review of innovative processes	Process	VR
Decision support system[41]	Assist monitoring and control of operations	Process	GIS
MBA-block building[42]	Safety planning considering environmental conditions	Process	GIS/4D CAD
Patterns execution and critical analysis of site-space organisation[43]	Critical space–time analysis	Process	4D CAD
Rule-based 4D system[44]	Rule-based	Process	4D CAD
Mäntylinna building[45]	Visualisation	Process	4D CAD
Safety analysis of building in construction[46]	Structural analysis	Process	4D CAD
Construction hazard assessment with spatial and temporal exposure[47]	Construction job safety analysis and evaluation of operational risk levels	Operation	4D CAD
Automated obstacle avoidance support system[48]	Sparse point cloud	Operation	Laser range scanning technology
Real-time proximity and alert system[49]	Generate active warning or feedback in real time	Operation	Wireless and RFID communication
WiFi-based indoor positioning system[50]	Indoor positioning	Operation	Wireless and RFID communication
Video rate range imaging system[51]	Detect, model and track the position of static and moving obstacles	Operation	Video laser range scanning technology

The ‘product’ indicates the building and infrastructure design. As discussed below, one system – named the design for safety process (DFSP) – applied VR and database technologies to assist users in identifying potential construction risks inherent in the design at the construction stage.[19,39] Substantial efforts have been made at the process level to improve safety. Almost all of them take advantage of 4D CAD to analyse on-site dynamics to enable safe project delivery. BIM and GISs have also been used in conjunction with 4D CAD to better understand construction safety issues by considering environmental impact and design information. At the ‘operation’ level on the construction site, 4D CAD has been applied through the construction hazard assessment with spatial and temporal exposure (CHASTE) tool, described below, to analyse detailed safety information;[47] and the computer image generation for job simulation (CIGJS) system,[38] which proposes photorealistic VR and the use of avatars for job safety analysis.

Online databases

Online databases have been developed to assess competence and to detect potential risks and hazards. A prototype online system has been developed by Yu[36] to help clients assess the competence of potential CDM co-ordinators, designers and principal contractors. The UK’s CDM Regulations 2007[13] and its Approved Code of Practice[52] established ‘core criteria’ to guide the client in assessing these duty-holders’ health and safety competence at the outset of a project. The web-based tool uses artificial intelligence (AI) to support their decision-making through this competence assessment processes, which may involve regulation checking, risk identification and control, incident information capture and analysis.

The construction safety and health monitoring (CSHM) system[37] was created to detect potential risks and hazards by enabling the user to monitor and benchmark selected health and safety performance parameters over time, displaying the results in graphical and tabular form. On a project, the tool displays an executive summary of data that are input by managers. The summary highlights the total accidents, fatalities and complaints, as well as related statistics on lost work days, monitoring and compliance activities, education and training, inspection, audit and prosecutions. The tool can also graphically display trends in the number of reported accidents and complaints received, and can be used to compare these trend results between projects. The research team developed CSHM as an internet-based tool to enable rapid input and output of data, with the aim of enabling managers to use results in decision-making, eg identifying areas of construction activities that require immediate corrective action.

Virtual reality

The term ‘virtual reality’ (VR) is used to describe a set of hardware and software technologies that provide interactive, real-time, 3D computer applications.[53,54] These technologies have been used to train construction professionals in a risk-free and realistic virtual construction site, eg the Building Management Simulation Centre.[55] Hadikusumo & Rowlinson[19,39] adopted VR for construction safety research by creating the DFSP database. This VR-based DFSP tool helps to identify safety hazards that are produced during the design phase and inherited in the building construction phase. It incorporates a theory of accident causation that lists common unsafe acts and conditions in the investigation of safety hazards.

Hence, the DFSP contains a ‘construction component/object type’ and an ‘accident precaution’ database. The former has all construction component/object types used in virtually real construction projects, such as beam, wall, column, slab, pre-cast slab and pre-cast stairway; the latter encompasses all possible precautions that can be used to prevent the occurrence of an accident. For the purpose of user interaction with virtually real construction components, processes and the DFSP database, four VR functions are provided in the system: collision detection, terrain following, geometry picking and 3D tape measurement. These functions enable a better walk-through environment, more accurate modelling of falls from height hazards, object picking to trigger the DFSP database and, because some of the safety regulations state required dimensions, measuring the dimensions of an object for the purpose of identifying safety hazards. This VR system features 4D modelling and a limited knowledge-based function, but still requires a human expert to direct its operation.

The virtual construction laboratory (VCL)[40] is a knowledge-based VR system that was developed in Hong Kong to enable construction planners to conduct virtual experiments of innovative construction technologies and processes. The motivation for the work was the adoption of innovative new construction methods which had not been previously used or tested. While the VCL does not explicitly address safety issues, it enables the planner to evaluate and validate planning before construction begins by dynamically visualising the construction site environment. Its use depends on requires models of plant, non-plant and buildings, as well as databases of plant behaviours (paths of motion, loading capacity and so on) and labourer productivity in performing different construction operations. The system can be programmed to provide guidance and assistance in planning and layout, site operations and arrangement – eg by warning the user where activities are not in the right sequence – and be extended to address safety issues in the construction process. While in the example given in the study these are developed manually, the broader use of object models that is associated with the increasing use of BIM suggests opportunities to combine existing object libraries and datasets, and to use automated rule-based checking within them.[56]

The CIGJS system[38] supports job safety analysis by applying VR technologies to generate a virtual human 'worker'. Because this analysis technique derives from manufacturing, where roles are tightly defined along an assembly line, it has limitations in a proactive risk analysis of new tasks or work conditions within construction. Modifying the technique to construction, CIGJS seeks to provide realistic simulations of actual work situations, contributing to job safety analyses to improve their effectiveness and usability in routine work situations, including construction work at an operational level, and to make the use of job safety analysis possible at the design stage. The features of CIGJS include virtual images, animation and a 3D interactive environment. A parametric virtual worker is applied in the system to describe a human body and workers' skills in a photorealistic VR environment. The new approach of job safety analysis combined with CIGJS permits an easier, faster, and much more intuitive analysis of the hazards potentially present in each sub-task, and their effective control. The workers themselves play an important role in defining the simulation parameters, thus actively contributing to the health and safety of the specific workplace they are already working in or in which they will operate. It has great potential in the field of education and training of workers on correct and safe working procedures.

Geographic information systems

Geographic information systems (GISs) provide an approach to considering construction safety from the macro perspective as they contain detailed information regarding the environment. In the MBA-block building project in India, Bansal's[42] motivation for applying a GIS to safety planning was the influence that environmental issues – such as site topography, thermal comfort and access route planning – have on worker safety. These environmental factors cannot be modelled with BIM and 4D CAD because they lack geospatial data by using GIS. The work facilitated 4D modelling, geospatial analysis and topography modelling in the development of safe execution sequences. A 3D model was developed along with its surrounding topography and schedule, and these were linked together within the same environment. During the safety review process, if a planned sequence results in a hazard situation, it may be corrected within the GIS itself before actual implementation. The research also discussed the use of GIS in the development of safety databases from which safety information can be retrieved and linked with the activities of the schedule or components of a building model. The combination of 4D modelling, along with topographical conditions and a safety database in a single environment, helps safety planners examine what safety measures are required when, where and why.

GIS was also integrated into a decision support system (DSS) to assist construction engineers in safety monitoring and controlling excavation conditions.[15] In this work, the authors consider foundation excavation as one of the construction activities prone to hazard conditions, and apply safety-oriented instrumentation programmes to address design issues. The DSS provides safeguards by indicating behaviour about threshold limits, and warning of any adverse effects of construction. The tool mobilises the 'reasoning' engine, along with the graphical displays of information in the GIS, to help the project manager monitor and control the excavation progress.

4D CAD

Four-dimensional computer-aided design (4D CAD) is used to simulate dynamic operations, such as the site operations involved in the construction of a building. Space–time conflict analysis using 4D[57] reveals that on-site workspace congestion can result in multiple clashes, including design conflicts, safety hazards, access blockages, damage, space obstructions, work interruptions and so on. Mallasi[43] applied entity-based 4D CAD technology to detect workspace congestion in order to identify potential on-site safety hazards. The research approach to detecting space–time congestion utilised critical space–time analysis (CSA) in 4D visualisation. This associates certain visual features for workspace planning with the workspace competition between different construction activities. It deals particularly with analysing this space–time competition that occurs between activities. The research focus is to quantify the nature of this competition by assessing the criticality of the workspace conflicts between activities sharing the same execution space. A key assumption in the research is that the dynamic nature of workspace usage and change are traced continually to accommodate space connectivity in the fourth dimension. Once the space connectivity mechanism is established, it is possible to quantify the particular effect of critical spaces on the progress of construction work. The patterns execution and critical analysis of site-space organisation (PECASO) prototype was developed in this work to encapsulate and evaluate the outcome of the CSA.

Benjaoran & Bhokha[44] demonstrated a rule-based system for safety and construction management using the entity-based 4D CAD model. The system targeted the working-at-height risk because falls were the most frequently occurring types of construction accidents, resulting in fatalities or severe injuries.[58,59)] Fall accidents accounted for the largest percentage of all recorded accidents, about 52 per cent, and are often associated with workers on roofs, scaffolds, ladders, and floors with openings. The study aimed to formulate a rule-based system that automates the process of identifying hazardous situations. Many factors related to details of both building components and activities (ie component type, dimension, placement, working space, activity type, sequence, and materials and equipment) are used as input data. These factors are examined systematically to find any working-at-height hazards. After hazards are identified, the rule-based system suggests safety measures, including safety activities or requirements. While being implemented, the rule-based system can be updated and maintained by the safety officers. The rule-based algorithms for working-at-height hazards are formulated, embedded and visualised in the 4D CAD model.

Advantages of the rule-based 4D safety system on a project include the ability to:

- identify working-at-height hazards at the various stages of the construction project
- articulate the hazards associated with particular combinations of building components and construction activities
- give advice on safety measures
- integrate safety measures into the construction schedule
- enable people to reveal problems in the original design and schedule
- support the control of safety measures.

Nevertheless, the limitation of this research using an automated approach is that a hard-coded algorithm is closed, and cannot make complex design decisions that need human creativity or knowledge to be involved in some circumstances. Applying open-ended, knowledge-based, interactive approaches can compensate for this weakness. Hence, expert knowledge in risk identification and hazard prevention can be updated, and human creativity is afforded the opportunity to be applied during design decision processes.

To forecast safety risks in construction projects, Rozenfeld *et al.*[47] created an automated tool named CHASTE to analyse various on-site risks at appropriate levels of detail and reliability for different planning windows and managerial purposes. CHASTE accounts explicitly for the fact that construction workers are frequently endangered by activities performed by teams other than their own. The risks to which workers are exposed change through time, as the activities performed and the physical environment of construction sites change. Because intensive hazard analyses at construction sites are rarely performed,[60] and hazard identification levels are often far from ideal,[61] CHASTE is a suitable tool for predicting risk levels in support of proactive safety management on construction sites. It is a time- and space-dependent model that can quantify risk levels by means of automated calculations, which enables more efficient management of construction safety.

The job safety analyses of common construction tasks in CHASTE are carried out using the construction job safety analysis (CJSA) method,[62] which is an extension of job safety analysis. The CJSA knowledge base must be prepared for each national or regional construction industry because it is dependent on local working culture. The use of loss-of-control events is critical in CHASTE as every work stage within each activity performed on a construction site has numerous typical ‘loss-of-control’ events, such as ‘dropping a tool’, ‘falling from a ladder’ or ‘formwork collapse’. Each such event has a distinct likelihood of occurrence dependent on team size, skill, space, climatic conditions and various other factors. The CJSA contains a substantial knowledge base of loss-of-control events and their probabilities for most of the activity types which are common in reinforced concrete construction. A limitation in the CHASTE process as presented is that no human factors, such as short eyesight or sickness, were considered in computing the probabilities of loss-of-control events. The VTT Technical Research Centre of Finland reports ongoing research and development of BIM-based safety management and communication system.[45,63] BIM-based 4D CAD was utilised as a central technology for construction site safety-related planning activities. It presented how 4D site layout and safety-related planning activities can be carried out using the BIM software, Tekla

Structures. It also identified opportunities to promote safety with the help of 4D BIM by involving partners such as designers, contractors, safety specialists and occupational healthcare personnel. The research aimed to develop and test solutions for the planning and management of construction site safety using dynamic 4D site models. For testing, the researchers chose the completed Mäntylinna residential building project by Skanska to examine railing safety issues in construction. Construction schedules were linked with the building parts, temporary structures and site production equipment.

One of the advantages of the research was the possibility of improving construction safety using commercially available BIM tools. Tekla Structures was selected for the 4D BIM work not only because of its sophisticated 4D functions, but also for its real structural model of the building project as a basis for safety planning. This model corresponds to construction work on site, including assemblies as the building is designed. As part of the modelling and visualisation tests, a set of suitable visualisation rules was developed for safety equipment used on a temporary basis. The rule-set can be used and developed for different purposes in pilots. Disadvantages are that safety-related custom components for the selected modelling software had to be developed in the project, and the needed, but missing, site layout and safety planning components created in co-operation with the contractor. The research showed that BIM models created in the design process can be developed to serve site and safety planning by adding the planned temporary site and safety arrangements to the model created in the architectural design or structural engineering stages.

Research on a safety analysis of building in construction (SABIC) system applies 4D BIM to the analyses of structural safety during construction processes.[46,64,65] This work identifies building structure and safety analyses that can be carried out at several points during the construction process, rebuilding static structural models manually at each point, and conducting probability-based calculations. Not only the structure but the material behaviour and loading conditions change dynamically during the construction process. To address this, the research analyses building structure safety based on the theory of Bayes dynamic linear model[66] during the construction process. Applying Industry Foundation Classes (IFC), the system converts a BIM-based architectural model into a BIM-based structural model with extra information of construction process, resistance model, and loading conditions for time-dependent structural analysis. The research highlighted a concern about structural safety during the construction process, which added another dimension in construction safety considerations. Further enhancement of the system lies in improving the accuracy and efficiency when generating a structural model from architectural model; analysing support system; and automatic alteration of the construction plan according to the results.

Sensing and warning technologies

Advances in information, sensing, visualisation and spatial temporal analysis technologies are enabling new forms of spatial awareness of construction job site conditions.[51,67] Combined with effective management practices, these technologies have the potential to decrease safety risks on job sites at an operational level. Teizer *et al.*[68] summarised the related technologies, approaches and their features. The basic idea behind these technical approaches is that job site safety risks can be improved by detecting, modelling and tracking 3D boundaries around hazardous zones, and then by classifying and separating them from the active construction workspace. Kim *et al.*[69] described the sparse point cloud approach to modelling static objects or zones that might cause danger or are proven to have hazardous potential. Applying this approach, McLaughlin *et al.*[48] created an automated obstacle avoidance support system to allow machines to navigate and operate safely.

In order to detect moving resources such as machines, workers or materials within the workspace, location-sensing techniques such as radio frequency identification (RFID),[70] ultra-wideband (UWB) nodes[71] and Global Positioning System (GPS)[72] are applicable. Video rate range imaging is a technique to rapidly detect, model and track the position of static and moving obstacles from a static or moving sensor platform.[51] In obstacle avoidance systems, it uses video laser range scanning technology to rapidly detect, model and track the position of static and moving obstacles. An experimental study demonstrated that position, dimension, direction and speed measurements had an accuracy level compatible with the requirements of active safety features for construction. The combination of this approach with other sensing and information technologies, such as 4D CAD, GPS, RFID and GIS, promise to improve construction engineering and management in methods, material tracking, visualisation and automation.

These technologies can be also used to create active warning systems to protect workers from risk situations in dynamic construction sites. Commonly available personal protective equipment (PPE) –

such as hard hats, safety shoes and goggles – provides passive protection only, whereas active warning systems can generate warnings or feedback to the worker when risks come into range. Teizer *et al.*'s[49] study of the application of real-time proximity and alert technology for daily construction operations using radio frequency proved the effectiveness of the proposed approach to enhancing safety in the construction environment.

These applications, however, still suffer from numerous shortcomings. Teizer *et al.*[68] highlight the fact that any wireless devices for obstacle avoidance system applications require tagging of each individual resource on a job site (human, material and equipment). Accordingly, the approach is unreliable where there are incidents involving untagged or misidentified resources. Other potential problems include poor signal strength through obstructions resulting in lower performance, the unavailability of GPS satellites or contact to a base station to determine precise locations, and the high cost of tags.

Tools to examine safety implications of the designed product

Digital approaches to construction safety in the design phase are less mature than those in the construction phase. Compared with the range of digital applications for safety in the construction phase, few tools are available in the design phase to help designers achieve construction safety. Apart from the DFSP tool that deals with design issues at the construction phase, there is significant work on a knowledge based design decision toolkit, and on using BIM to enable construction safety by design through rule-checking approaches. An overview of the tools found in this review is given in Table 3.

ToolSHeD[73] is a web-based design decision tool to provide decision support for construction professionals, and help assess the risk of falling from a roof during building maintenance work. Underlying ToolSHeD is a knowledge-based approach to assessing the maintenance risks of complex building situations. Knowledge acquisition was from data sources, including Australian occupational safety and health guidance material, industry standards and codes. An expert panel evaluated acquired knowledge to validate its effectiveness. On the basis of this work, acquired knowledge was modelled in a series of logic diagrams called 'argument trees', which represent a template for reasoning in complex situations. These diagrams provide a practical way of representing knowledge when the outcome being considered is subjective and interrelated with other issues that need to be considered simultaneously. Through its web-based user interface, the ToolSHeD provides a step-by-step approach to the assessment of the risk of falling from heights presented by features of a building's design. The risk assessment prompts designers to enter information about relevant design features that experts agree could impact on the risk of falling from height. The data entered are then used to infer a risk rating based on a reasoning model agreed by the panel of experts. A risk report is generated as a system output to advise the designer about level of risk of falling from height (extreme, high, medium or low), and an explanation of the design factors contributing to this inferred level of risk.

Table 3
Digital tools for construction safety design

Tool/Project and citation	Approach	Level	Technology	Advantages	Disadvantages
Design for safety process[19,39]	Simulation and review	Process and product	VR	Simulation and review of construction process for design-related safety issues	–
ToolSHeD[73]	Knowledge base	Product	Web	Web-based system suitable for multi-party collaboration; combines with regional health and safety regulations	Not integrated with design information; applicable only for maintenance phase
Knowledge-based safety design analysis prototype[74]	Rule-checking	Product	BIM	Integrated with design information; combines with regional health and safety regulations	Limited Internet functions for health and safety rule browsing; not for collaboration; applicable solely to maintenance phase

The HSE reports that falls on building sites and during maintenance are the largest cause of accidents at work in the UK.[75] To address this problem, NNC Ltd worked with AEC3 UK Ltd and buildingSMART UK to demonstrate a knowledge-based prototype system in which proposed buildings can be tested against health and safety requirements that are graded according to levels of risk. In a pilot project in Singapore, the prototype system focused on ‘roof lights’ because the risk of a fall from the roof of a building is frequently associated with their installation and maintenance. A set of rules was defined for the automated assessment of safety involving knowledge of the roof, roof light, and handrail objects, the building, the site as a whole and the relationships that exist between these objects. The project used software technology developed for automated building code checking. BIM systems were used to export data in the IFC format to a database. Data were then tested against rules that were defined following consultation with health and safety experts, as well as against regional health and safety rules. Reporting the results of completed checks was achieved through graphic and rule-browsing software, provided by NovaSprint Pte Ltd, that allows controlled viewing of the building by object and by rule.

These safety design tools consider safety in design to improve practices in construction and maintenance. They have different advantages and disadvantages, as shown in Table 3. The ToolSHeD system adopts regional health and safety regulations to guide risk analysis. It utilises the web platform and hence is suitable for multi-party collaboration across the Internet. However, geometric design information of a building is not incorporated into the system. This makes it only useful for risk analysis in the maintenance phase rather than the construction phase. The NNC’s knowledge-based prototype takes advantage of design information from BIM for rule-based checking. Its automated rule-checking approach is based on the incorporation of regional health and safety regulations. Yet, it only targets the maintenance phase for risk analysis but not for hazard prevention in the construction phase. Its Internet-based functions are applied for browsing online health and safety rules instead of multi-party collaboration.

Given the value of considering construction safety through design as discussed in section 2, the review of this strand of literature, in this and the preceding section, reveals a relative lack of digital tools to support it. Digital tools have been developed for managing construction safety within the construction phase, but few are available to support design for construction safety. Hence, the review of this strand of the literature suggests particular opportunities for research to develop tools to support construction safety through digital design, especially in the context of the wider emphasis on design in policy-making in the UK and elsewhere.

Practices in construction safety and digital design

The second strand of research is a literature that empirically studies practice, within which authors have examined safety-critical operations, practices of using technologies, and design practices. This literature draws on wider theories of organisation and starts from essentially different assumptions and research traditions to the first strand. Here, safe working practices are seen as an emergent feature,[17,76] negotiated in the context of fragmented and antagonistic safety cultures,[77] and influenced by the patterns of authority and learning on construction sites.[15] Within everyday practice:[78]

> … conflict between forms of authority and knowledge can inhibit the dissemination of good safety practice: initiatives will meet significant resistance if they contradict the experiential knowledge of site operatives; if they do not make use of this experiential knowledge, they may fail to address hazards fully; methods of site learning, particularly in the development of innovative practice, are inherently hazardous.

Thus, the focus is on the divergent forms of knowledge within complex organisations, rather than individual error. Systemic accidents are described by Perrow[11,79] as normal (but rare) within complex organisations because they have non-linear and multiple interdependencies between their sub-systems. He sees complex organisations dealing with incompatible needs for centralisation, to cope with the tight coupling and interaction between sub-systems, and for decentralised decision-making to manage and contain problems in ongoing operations. Hence, work in any system deals with danger and failure, as well as safety.[77] Accidents are described as ‘normal’ as, paradoxically, tight coupling in complex organisation is needed to manage interaction risks; and loose coupling is needed to manage risks that arise in ongoing operations.[79] In ongoing operations within such contexts, heedful inter-relating or ‘mindful’ action are essential to challenge assumptions, check and validate proposed solutions, as well as to make sense of and respond to unexpected situations that arise.

The introduction of digital technologies is seen as having both intended and unintended effects. For example, technologies are often introduced to increase managerial oversight and control.[80] Yet, as they take control away from workers, digital technologies can hinder their 'mindful' action, increasing the potential for mistakes and accidents.[81] Often digital systems do not encourage the active challenging of assumptions, checking and validating of solutions across sources and ongoing sense-making. Weick argues that:[82]

> It is the very self-contained character of the electronic cosmos that tempts people, when data make less and less sense, to retain assumptions rather than move to different orders of reasoning.

Hence, digital technologies may lead to errors by increasing 'mindlessness' as:[83]

> Reliance on a single, uncontradicted data source can give people a feeling of omniscience, but because these data are flawed in unrecognized ways they lead to nonadaptive action.

While much of this existing research has focused on operations, in safety-critical contexts such as nuclear power and space exploration, the insights it provides are also relevant to design.

This work has a particular relevance to the challenge of considering construction safety in design, where forms of knowing through written reports and documentation are dominant in the professions; and forms of knowing through experiential learning are dominant in the trades.[14,15] Within the construction industry, some activities across design and construction are becoming more tightly coupled through the use of BIM technologies;[85–87] while the use of digital technologies is also changing communication patterns in other parts of project organisation by presenting data in formats that are not accessible to all members of the team. In the discussion of risk in the conceptual stage of projects, it has been argued that:[88]

> … the use of information technology and integration of various information systems appear to have a more positive influence on the use of risk management in the conceptual phase of a project life cycle than the type of organization structure.

More research is needed to examine the relationships between digital design and construction safety and to examine where and how these lead to mindful or mindless practices.

In summary, at the same time as research in the first strand has developed novel ways to use digital technologies in addressing safety issues in construction, this second strand of research raises a concern about 'mindlessness' in the broader use of digital technologies, which can have unintended and negative impacts on safety. This literature suggests a need for further research to investigate relationships between construction safety and digital design, and, as we argue later, ways of engaging with end-users and different forms of knowing throughout this process. It has implications for research in the first strand that looks to develop new tools that specifically address safety. For example, it suggests that systems must encourage users to check and make sense of unexpected data rather than rely on managerial oversight.

3 Research methods

Bringing the strands of this review together suggests new kinds of interventions, such as the development of tools and processes for multi-party collaboration on safety around digital models. These tools and processes do not attempt to provide a 'complete solution' to safety issues. Rather, they will be judged by the extent to which they foster the consideration of safety through the kind of 'mindful' actions that challenge assumptions, check and validate proposed solutions, and make sense of and respond to unexpected situations that arise.

The design of this study is suggestive of new directions of research on construction safety and digital design that could focus on technologies that enable constructors to share their knowledge with designers, using the visualisation potential of new technologies to bring knowledge of the construction site into design.

Consultation with industrial partners

Industrial partners were involved in the research through: visits to their offices in the early stages of the work; their visits to the team and participation throughout the project; feedback and reporting of findings; and discussions on the direction of future research. Details of the interactions are listed in Table 4.

Table 4
Participation of industrial collaborators

Interaction	Date	Roles of participants	Purpose
Visit from construction contractor A	June 2010	Head of Design; Head of CAD; Head of Multimedia	Understand our work on building safely by design
Visit to construction contractor B	July 2010	Design Director; Environmental Adviser; Health and Safety Adviser	Gain industrial comments on experiment design
Visit to a modelling consultant	July 2010	Director; Engineering Services Developer; Lead Design Co-ordinator; Technical Manager	Collaboration on safety and visualisation, ie model 1 provided to the research team
Hosted visit from experienced industry professional	Nov 2010	Director	Build on industrial and academic research on modelling and safety
Hosted visit from engineering modelling consultant	July 2011	Two Directors; Lead Design Co-ordinator; Technical Manager	To visualise and discuss the provided model and pilot experimental protocols
Visit to construction contractor C	May 2011	Environmental Health and Safety Manager; Safety, Health, Environment and Quality Director; CDM Co-ordinator; Architect	Collaboration in the project and the safety issues that arise on construction sites
Visit to an engineering design consultant	May 2011	Researcher; Accessible Environments Leader; Visualisation Manager	Collaboration and arranging access to a design model for project 2
Meeting at site office of project 2	July 2011	Project Managers (for projects 2 and 4) from contractor D; Company Health and Safety Managers	Collaboration and discussion of site safety in relation to project 2
Hosted visit from contractor C	Aug 2011	EHS Manager; CDM Co-ordinator; Architect	Experimental participation with independent evaluations of model 1 and co-discovery
Hosted visit from designers and contractor E on project 3	Sept 2011	Senior Engineer; Construction Manager; CAD Manager; CAD Technician; Planner; Design Manager; BIM Co-ordinator	Wide-ranging discussion of model for project 3 at stage D in the design
Hosted visit from project 2	Mar 2012	12 industrial participants from contractor D and projects 2, 4 and 5	To visualise design model and get feedback on our research on the connections between safety and design on their project

While these interactions were not conducted under experimental conditions, they significantly enriched the project by bringing in extensive practical experience of safety issues and concerns that arise on site. To get to know the practitioner communities interested in digital technologies and safety, the team also attended IOSH events – in Edinburgh on 24 March 2010 and in Hull on 18 January 2011 – and presented the aims of the project at a Construction Mobile Information Technology event in Manchester on 09 June 2011.

Laboratory set-up

Model and virtual scenarios

A set of virtual scenarios for use in the CAVE were built from an existing model of a hospital design, which was provided by an industry collaborator. The collaborator had provided construction detailing and design development support, creating a 'federated model' of structure, services and architecture, between RIBA Stages F2 and J. Rather than focusing on mechanical, electrical and plumbing (MEP) and finishing works (as had been the original intention), the scenarios developed in the University focused on hazards in which the permanent design might have an impact on safety on site. This change in emphasis came about through discussion of the proposed work with the IOSH Research Committee, with participants in IOSH meetings and with experienced safety professionals in construction contractor C (see section 4).

The hospital model (model 1), provided by an engineering modelling consultant, was the main focus of the work to set up the experiment. This model shows a building that is three storeys high, with a conventional concrete frame, and with more ducts for services than there would normally be in a comparable office building. For the purposes of this exercise, the project researcher identified nine examples of design pitfalls and their related risk scenarios (listed in Table 5). These illustrated safety issues related to roofing and structures, with a focus on issues that could result in fatalities: either through a fall from height or being struck by a moving object. The CHASTE database[89] was used initially to identify zones in which there were challenging construction operations from a safety perspective. Within the CHASTE approach, risks are a function of the likelihood of loss-of-control events during work execution, the probability of exposure of workers to those events, and the severity of the potential outcomes. However, given the nature of this research, the professional safety design guidelines/checklists in the 'Design for Construction Safety Toolbox',[30] which lists a wide variety of typical design errors, along with the hazard types to which they most commonly lead, were used to compose the list of common design pitfalls and associated hazard types.

No.	Design	Risk scenarios
1	Low parapet	A low parapet presents a risk of falls from a height for those working on the roof
2	Closely spaced openings	Closely spaced openings are a hazard because they leave limited safe space for operations
3	Missing guardrail around the roof access	A lack of guardrails as protection around the roof access presents a hazard around the stairs
4	Steep roof pitch	If not adequately addressed in planning, workers or objects are at risk from sliding down a roof
5	Missing fall protection	The lack of permanent guardrails or anchor points can make it difficult for workers to perform operations safely
6	Missing covers over exposed openings	The lack of covers on exposed openings presents a risk of falls from a height
7	No attachments or holes in structural members	The lack of these features at elevated work areas presents a risk of falls, for example if there are unstable scaffolding connections with structures
8	Missing foot boards on a scaffold	The lack of foot boards on scaffoldings presents a risk of falls
9	Moving crane with load where workers are present	The crane carrying a load is dangerous when workers are present below the working range

Table 5
Nine design pitfalls and their related risk scenarios identified in model 1

Modelling work was done to present these risk scenarios, using:

- a static 3D model to visualise the building product
- dynamic 4D modelling to visualise the construction process
- a simulation of dynamic crane operation to visualise operations.

Additional 3D graphic objects were created to represent the changing reality during the construction process, in terms of temporary facilities and construction equipment, and intermediate stages of the building, with stairs, scaffolding, a crane and a prefabricated steel truss added to the main structural model to help generate related risk scenarios. The construction operations scenario that was modelled was of the crane lifting the steel truss from the ground to the roof. This example operation raises a series of concerns in safety design and safe process delivery. The product, process and operation models were used by the experiment participants to identify and discuss related risks and the potential for designers to reduce incident liability.

Visualisation and recording media

Three main visualisation platforms were used in the experiments: a CAVE, a desktop widescreen display and personal computers. The ambition was to identify effective modes of conversation and behaviour across platforms not only to explore advanced visualisation capabilities, but also to develop guidance for communication between builders and designers in design for safety review sessions in everyday work situations, supported by accessible visualisation tools.

First, a CAVE platform was used for the co-discovery sessions with industry participants. The CAVE at the University of Reading is an immersive VR system consisting of a floor which is a 3 x 3m square, with images projected from the top, and three walls, which are 2.2m high and constructed from rear-projected display screens. The basic functionalities of the University of Reading CAVE were developed with the VieGen set of tools, developed at the University, which enable rapid development and prototyping of immersive virtual environments. For display in 3D in the CAVE, the building and construction site model was converted into Virtual Reality Markup Language (VRML) for import. Professionals inspecting the scaffolding in the CAVE are shown in Figure 2.

In the co-discovery experiments in the CAVE, a researcher served as ‘navigator’ for the team of participants (a designer and a builder), using a hand-held joystick to perform 3D walk-through, viewing it from the positions or angles requested by the participants. A virtual pointer controlled by the lead observer was also provided, and this was free to be used to highlight areas of interest and assist collaborative discussion. Further buttons on the joystick were used to switch the users between

Figure 2 Safety professionals inspecting a scaffolding scenario in the CAVE

different phases of the dynamic 4D construction simulation. A video camera was operated during the pilot test. As the video operator filmed from outside the CAVE, the footage captured the collaborators' conversations, their interaction with virtual objects in the model, and their behaviours. Captured videos were then processed as movie files by the computer for further data analysis.

Second, the desktop system involved three monitors connected to a desktop PC via a Matrox Triplehead2go adapter. The desktop widescreen display extends users' horizon from a normal screen to the larger triple screen, and thus provides more field-of-view based on a relatively low-cost system. The project researcher controlled the system using a standard mouse and keyboard for interactive operations such as 3D walk-through and 4D simulation.

For the experiments conducted in the desktop widescreen display, a screen-capture software tool – BB Flashback Express – was applied to capture a dedicated screen region or window. Interactive operations on the screen were recorded and synchronised with audio recordings of the collaborators' discussions. The recorded videos could be played back directly in an integrated environment for editing and experimental data analysis, as shown in Figure 3.

Third, the visualisation for the individual assessments used the 3D capabilities of Adobe PDF documents. The 3D model could be viewed through the embedded browser and users could walk-through, rotate, move, zoom in/out, and fly-through the model. This enabled individual participants to access a model through their own computer, without requiring special software or hardware.

Experimental data collection

Industry participants

Two tests were conducted with industrial participants. Participants initially completed an independent design review assessment, and then conducted co-discovery sessions in the CAVE (as discussed in sections 1 and 3, and shown in Figure 1). The first test, in February 2011, was performed as a pilot with three members of the engineering modelling and visualisation consultancy firm that had provided the model. One had experience in construction (a 'builder') and the other two were designers. The second test, in August 2011, was with two safety professionals from major construction contractor C. Individual assessments were recorded in note form, and the co-discovery sessions in the CAVE were recorded, transcribed and analysed.

It took some time to familiarise industrial collaborators with navigation in the CAVE, and the project model used in the experiment (model 1) was also unfamiliar and incomplete. Each experiment required four to eight hours to conduct. This made it difficult to choreograph more than one experiment during each visit. Two strategies were taken to address this in later work. One was to use graduate students who have experience of working in design and construction roles within the industry in completing a set of experiments with model 1. The other was to engage whole project teams in discussing models of their own projects. In the latter mode, we hosted a number of industry visits to the CAVE, including that of designers and contractor E from an underground project station team. The second of the two industry tests with the hospital model is reported in detail in section 4.

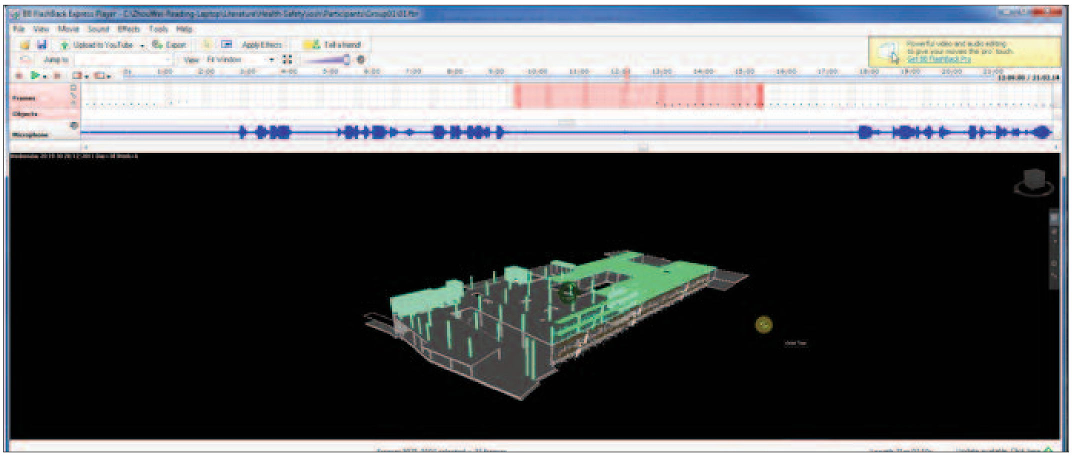


Figure 3
BB Flashback Express screen capture system

Graduate students

The project researcher engaged graduate students, mainly from the MSc in Construction Management at the University of Reading, in independent assessment and co-discovery sessions in November and December 2011. In their individual assessments, these 47 students (44 MSc and three PhD) performed a design review and recorded the safety risks they identified. They were asked to indicate their backgrounds in architecture, construction or other disciplines. Two of the PhD students had done this independent assessment as part of a pilot of the whole process. Eight of the 44 MSc students identified themselves as having a background in 'architecture', including one who specified that they were a 'designer'; 21 stated they had a background in 'construction', including one who specified 'civil engineering'; and 15 described themselves as 'other', two of whom specified 'quantity surveying'. One further individual – a PhD student with a background in architecture – also completed this independent assessment.

The individual safety risk assessment asked participants to identify the safety hazards in the product, the process and the operations. For each hazard, they were asked to report the building component involved, to take a screen-shot from the model used in their individual assessment to show the location, and to describe in words the problem that they identified. Excluding 10 responses that left an unmodified version of the example risk on the returned sheet (eg roof, image, no description), there were 347 responses from the 47 students, with each student thus identifying an average of seven issues (more than 90 per cent of students identified between four and 10 issues). The coding and interpretation of these responses proved challenging, and the assessment results were coded more than once.

First, they were coded broadly into product, process and operation risks, with a more detailed coding into the predefined categories that had been developed from the nine pre-identified risks (shown in Table 5) and additional categories that had emerged from the tests with industrial participants. However, this process involved qualitative judgments about the data that were not transparent. The steps taken in this coding were not documented, and an attempt to replicate the coding was unsatisfactory. As a result, the coding schema was abandoned.

The data were then coded descriptively, with each response classified according to its location, type, and hazard. This revealed a challenge in coding this data as to which responses to exclude. For example, in the first run of the second coding around location, type and hazard, the project researcher treated 59 answers (49 in addition to the 10 excluded above) as invalid. The results presented and discussed in section 4 of this report come from a second run of this coding, in which all 347 responses were coded (excluding only the 10 that included, but did not modify, the example given). The issues around whether respondents could validly identify safety issues are discussed in the interpretation of these overall results.

Selected MSc students and the PhD student were asked to engage in a subsequent set of co-discovery sessions in December 2011 to examine safety issues in designer–builder pairs on a desktop widescreen display. The eight MSc students who indicated they had architecture and design experience, together with the PhD student, were selected to role-play designers, with nine other MSc students, including two students who indicated civil engineering and quantity surveying backgrounds, selected as builders. The remaining 27 MSc students, who were not selected, each observed one of these sessions.

In March 2012, with the permission of the industry participants, the results of both industry and student experiments were fed back to, and interpretations discussed with, the MSc students to improve their understanding of safety issues. This group was also interviewed to provide additional background detail to use in further analyses of the individual assessments of safety issues.

Validity and methodological limitations

In the experimental work, a number of assumptions were made, eg that it was possible to use model 1, which visualised a structural model and temporary works features, as a prompt to discussions about safety. Even with the simplifications that were made to create experimental conditions, it was difficult to hold control variables constant and isolate independent and dependent variables. Hence, at times in the study the initial assumptions became contested and the analysis of data was revisited. For example, the idea of comparing results from the individual assessment with the collaborative assessment was not pursued as there would be some expected learning between these sequential assessments and a lack of the control group that would be required to measure the extent of this phenomenon.

For this reason, some of the data generated in these experiments have been discarded and are not reported in detail in this report. Where data are reported, the caveats and limitations are discussed.

The original assumption that relatively novice designers and builders would be able to identify safety concerns is tested by comparing the findings from the study of this group with the results of the sessions held with professional safety managers. To address concerns about the validity of these assumptions, the Design Innovation Research Centre Advisory Board suggested calibrating what professionals understand through the conversation around a digital model with data from a real construction site. This suggestion is taken forward in further work discussed in section 5.

4 Findings and results

Inputs from experienced professionals

Early discussions with two safety managers in construction contractor B identified practical constraints about the ability of designers and builders to have a shared discussion of the safety implications of design on ongoing projects. These constraints arise partly as a result of contractual arrangements. Under traditional 'design–bid–build' contracting arrangements, which are used in the majority of construction contracts, the design and construction stages are sequential, rather than parallel, with different stakeholders involved in the two stages.

While the safety managers felt that more connections needed to made so that designers and constructors could discuss health and safety, they also emphasised that design and construction involve totally different ways of working. When the designers do their risk assessment, there may not be a model or a schedule of how the building will be delivered. The CDM co-ordinator should be (but is not always) there at the very start, but the contractor often joins the team only after the tender process, ie once the design has been developed.

The designer does scope out the build, but this is often not how it progresses. They may, for example, ask the contractor to erect some scaffolding, but the contractor may decide to use a scissor lift instead. Contractors have a variety of safe procedures they can use, and within the contracting company there are specialists in temporary works and alternative solutions tasked with working out different ways of building the design. Often this construction team starts out by discussing issues that the designer has not thought of, such as how to get appropriate working space.

In the construction stage, the contractor does not always refer to the designer's risk assessment. The designer may not get feedback on the impact of design on health and safety on the site. One reason for this is that, during the construction phase, it is at the contractor's discretion to advise the designer of any changes that do not affect the end result. Subcontractors will often have a better understanding and more experience of health and safety issues, and can write a method statement to do procedures their way, integrating health and safety into their processes.

The safety managers suggested that the greatest potential for this approach might be in 'design and build' projects where both the designers and builders are involved, particularly around framework agreements, such as in the Academies programme in England, where 20 schools were built at the same time. There was a discussion about the increasing remoteness of designers from the site because of less direct client contact and changes in their responsibilities. The professionals also questioned the proposed focus on MEP and finishes, asking whether these were areas in which there was the most risk that could be addressed at the design stage. They argued that much of the challenge of MEP and finishes was around minor trips, slips, falls and clutter, and advised us to consider more directly issues around structures, excavations, foundations and cladding as matters that could be addressed in design.

Experimental results

Safety professionals discuss the design model in the CAVE

This section discusses how, following the modelling work (as described in section 3), two safety professionals from construction contractor C observed and commented on the design in the CAVE. First, they individually identified and discussed a set of risks, and suggested actions prompted by the design model (model 1) viewed on the desktop computer. They were then invited to view the model in 3D stereoscopic vision in the CAVE, where the model had been set up with predefined locations around the nine example scenarios outlined in Table 5.

While the individual assessments brought issues with the design to the surface, as represented in the model, the conversation in the CAVE is the focus of this analysis. Both professionals had individually picked up on and discussed the following range of issues:

- Roof and edge protection: the low parapet around the roof (both); the lack of anchor points on the pitched roof trusses (both); no permanent guardrail around the atrium; the guardrail on the roof should protect workers from roof edges; lack of covers on holes and openings (both); and under the openings that do not have covers, work may be taking place.
- Vertical transport: lack of a permanent handrail installed as a guardrail on the stair (both); for vertical transport it would be good to consider using a permanent staircase rather than scaffolding.

- Scaffolding and connections: no anchor point on the structure to tie scaffoldings; no footing supports for scaffolding; a board missing from the scaffolding; a brace missing to connect the independent gate with the main structure.
- Site layout and crane: the influence of weather on the site layout (both); no safety entrances and exits indicated on the site; the structure has no protection from a clash with the crane; a hoist would decrease manual work; the crane driver has a poor view, and it would be better to use the attached tower crane in the middle region.

The discussion of the 3D model in the CAVE centred around the:

a) voids on the middle floor
b) stairs
c) scaffolding and cladding
d) crane
e) roof
f) voids and edge protection on the roof.

In addition, the issue of edge protection was raised right at the beginning, before the research team moved to the first scenario, and was returned to many times throughout the conversation. Referring back to what was picked up in the individual assessments, this initial exchange was:

Professional 2: Did you pick up on?
Professional 1: Yeah, I did, a little bit of the drawing.
Professional 2: We both picked up on that!
Professional 1: A drawing of a hand rail […], all that kind of stuff.

The aspects questioned and discussed by the safety professionals are summarised in Table 6.

Overall, the assessment in the CAVE provided 44 minutes of recording for analysis. As discussed in section 3, this is a part of the dataset, representing one of the industry experiments, and is analysed in detail in this report. Some of the time taken in the experiment was spent in basic familiarisation with CAVE functions; discussion of modelling issues; swapping models; and navigation. Twenty minutes were spent viewing the middle and top floors and roof of a static 3D model, during which safety professionals identified the issues summarised in Table 6. Following the viewing of the static 3D model, the next 10 minutes were spent on a 4D model: initially, the whole sequence was viewed and then researchers revisited the sequence again, prompting the safety professionals to discuss different

Figure 4
Image capture from the video in the CAVE

aspects of the model and revisit and discuss issues. Finally, three minutes were spent specifically on the operation of the crane. In the 4D model and simulation of operation, the researchers led and prompted the conversation more than in the 3D review.

As shown in the Appendix, the professionals discussed ‘voids on the middle floors’. They not only articulated alternative solutions – running rebar (reinforcing bar) through the hole if practical, and considering making the permanent barrier as part of the construction process – but also assessed the value of the sense of physical scale that was obtained through 3D stereo projection. The two safety professionals took turns in the discussion of safety, with the research team helping with issues of navigation, where parts of the model were treated as artificially off-limits to constrain discussion to a set of pre-established scenarios.

As the conversation continued, it turned to the question of the staircase and ambiguities in the model, ie the purpose of vertical shafts was unclear given the information available. As the Appendix shows, the two professionals spotted an unprotected opening in the model, and they wondered why it was open. They thought it might be a shaft, a smoke extractor or a pressurised staircase. They then became quite sure that there was no reason to have it as an open void, and if there was a reason, it should have had edge protection. One professional wondered if there was the potential to use the permanent staircases for circulation during the construction phase, rather than having ladders in the scaffolding.

Table 6
Identified risks and aspects questioned and discussed by the safety professionals

Areas with risks	Duration of discussion using static model	Main topics discussed
Voids on the middle floor	5 mins 23 seconds	The unprotected nature of the voids shown in the model; the sense of scale given by the visualisation; techniques for managing voids, and their dependence on the span; the potential introduction of permanent edge protection as part of their construction; and connections between voids.
Stairs	1 min 55 seconds	The open staircase shown in the model; the need for edge protection; a potential use of the stairs for access during construction; designs and construction sequences to provide continued protection around the staircase.
Scaffolding and cladding	3 mins 24 seconds	Edge protection, and, as the model did not show this, the connection of the scaffolding and the building; cladding the building, and a potential void between the scaffolding and structure; set-out lines for cladding panels to work out where the scaffold ties need to go; the use of permanent stairs and scaffold lifts rather than the modelled ladder access up the scaffold; work area access.
Cranes	1 min 50 seconds	Lack of vision, as operator of the crane shown in the model wouldn’t be able to see what they are doing; use of a tower crane, which would be more appropriate as the crane driver would sit above the project with a bird’s eye view of it and have better access; integrity of the ground the crane is located on.
Roof	2 mins 15 seconds	Finish and construction process (whether prefabricated or built on site); suggestion that the roof could be moved into position by crane; edge protection; questions about whether the courtyard is open, as it is unclear from the model.
Voids and roof-edge protection	4 mins 40 seconds	Purpose of the various voids, and potential for rebar across them as a temporary arrangement; inadequacy of the fencing enclosure shown in the model where voids are outside the safe area; particular voids that might be air conditioning shafts; safe methods for their installation; need to understand function to make their design safe to construct and so avoid reliance on a man-safe system; whether the designers have oversized some of the voids.

The safety professionals were then guided by the researchers to another scenario within the model, and started to discuss the scaffolding and cladding. They picked up on the lack of edge protection around the scaffold, and asked questions about how it was tied to the building temporarily, and how that might work practically as the cladding was installed. In the dialogue there was some commentary on the navigation, as one of the professionals asked the researcher to move them to the right point in the model to get a closer look at the scaffold. The professionals presumed that there would be brackets to fix the cladding. However, there would be a gap until the cladding went on, where things could topple through. One of the professionals suggested that if the permanent stairs within the building could be used during construction, there would be no need for a scaffold lift. However, given the available information, they were not sure about whether a scaffold lift would be necessary.

The two safety professionals discussed how a tower crane would have significant advantages over the type of crane shown in the model. As the data in the Appendix show, in the modelled scenario the crane driver had an inadequate view of the site and hence would not be able to safely construct the roof. The professionals considered alternative types of crane (including a corner crane), agreeing that the best option in this situation would be a tower crane located in the courtyard within the building, which would not only allow the crane driver a better view of the operations, but also provide greater access to all parts of the site.

The two professionals then discussed the possibility of prefabricating the roof. As the dialogue in the Appendix shows, they felt that this was probably the best way to produce a roof of this size. Finally, the professionals identified that the openings on the roof were similar to the ones they suggested running rebar through. Their dialogue in the Appendix shows their uncertainty regarding the openings and their function. They articulated how they might be air conditioning units and were probably there for a function. If they could be moved, that would provide protection. They also noticed a lot of openings in the building and felt they needed more detail from designers as to whether all the openings were necessary.

The design issues and incompleteness of the virtual model prompted a process of 'scenario planning' by the safety professionals. As illustrated in the Appendix, the professionals effectively created a context for the project during their CAVE session interactions and projected a narrative of problem-solving by drawing on their experiences of 'real world' site-based events. For example, in a discussion of the ambiguities surrounding the scaffolding in the model, a safety manager remarked:

> You've got to find some way of tying this [scaffolding] into the structure temporarily, but how's that going to be faced with getting your cladding on? Actually, another point I've just noticed with that is I presume there'll be some kind of bracketry to fix your cladding and the distance between the leading edge on the scaffold.

Collaborative discussion around the lifting of cladding materials by crane, then, prompted the identification of further safety issues:

> So the issue with the crane becomes very obvious now […] we're right actually here […] the lack of vision is very obvious.

It is interesting to note the turn-taking and style of language used by the safety professionals in their interactions around the digital models and to reflect on how that shows a careful awareness of the limits of knowledge, where comments may be prefaced with remarks such as: 'don't know if this is relevant', and the dialogue moves between actors as safety issues are explored collectively and discussed.

Student participant results

As noted earlier, the 47 respondents to the individual assessments identified 347 safety issues in the model. The range of answers received indicates different levels of safety knowledge and competence. Table 7 shows the types of issue identified by the various categories of student, as well as the average number of issues identified per participant in each group.

While most of the graduate students identified issues around edge protection and openings in the building, most of them lacked the experience to discuss alternative types of equipment; prefabrication; or solutions such as the use of permanent staircases as circulation routes during construction. There was no discussion of alternative forms of crane in the individual assessments, with a tower crane identified as a better solution in only two of the 10 collaborative discussions. These findings were fed

Table 7
Issues identified by the student participants

Issue identified	Architecture and design (10 participants)	per participant	Construction and civil engineering (23 participants)	per participant	Others, including quantity surveyors (14 participants)	per participant	Total	Indicative prevention measures suggested, with the number of suggestions in brackets
Site and temporary works								
Crane	2	0.2	16	0.7	11	0.8	29	Barrier (1), Clear view (4), Fence wall (2), Guardrail (1), Pull back (1), Signs (16)
Scaffold	16	1.6	28	1.2	16	1.1	60	Barrier (1), Board (22), Entrance/exit (1), Footing (3), Guardrail (12), Netting (12), Not steep (1), Railing (3), Tie bar (1), Toe board (2)
Site	0	0.0	12	0.5	5	0.4	17	Barrier (1), Entrance/exit (1), Fence wall (4), Guardrail (1), Netting (3), Signs (1)
Entrances and circulation								
Canopy	1	0.1	2	0.1	2	0.1	5	Covers (1), Design (1), Guardrail (1), Model integrity (1), Netting (1), Ceiling (2), Covers (2)
Ramp	1	0.1	0	0.0	0	0.0	1	Guardrail (1)
Stair	2	0.2	16	0.7	9	0.6	27	Covers (1), Design (1), Guardrail (4), Parapet (1), Railing (14)
Exterior								
Courtyard	3	0.3	1	0.0	2	0.1	6	Barrier (1), Guardrail (1), Netting (2), Railing (2)
Curtain wall	7	0.7	10	0.4	2	0.1	19	Barrier (1), Fence wall (1), Guardrail (7), Netting (7), Railing (2)
Roof	20	2.0	33	1.4	25	1.8	78	Anchor point (4), Barrier(3), Covers (10), Design (1), Guardrail (26), Netting (2), Parapet (12), Railing (7), Signs (2)
Vertical spaces through the building								
Ceiling	0	0.0	1	0.0	1	0.1	2	Covers (1)
Elevator	3	0.3	7	0.3	3	0.2	13	Barrier (3), Covers (1), Guardrail (6), Railing (1)
Ground floor	1	0.1	7	0.3	3	0.2	11	Covers (2), Design (1), Lighting (1), Model integrity (1)
First floor	18	1.8	29	1.3	13	0.9	60	Barrier (5), Covers (7), Fence wall (1), Guardrail (14), Model integrity (2), Netting (6), Railing (13), Signs (5)
Second floor	1	0.1	0	0.0	2	0.1	3	Design (1)

Structure								
Internals	0	0.0	1	0.0	1	0.1	2	
Columns	0	0.0	4	0.2	6	0.4	10	Model integrity (5)
Foundation	0	0.0	2	0.1	0	0.0	2	Design (1)
Underground	0	0.0	1	0.0	1	0.1	2	Fence wall (1)
Total	**74**	**7.4**	**170**	**7.4**	**102**	**7.3**	**347**	

back into the classroom with results from the interactions with safety professionals informing the discussion, as well as feedback on the experiment with graduate students.

The analyses do not show a significant distinction between the safety issues identified by these different categories of graduate student. The additional data obtained suggest that this may be partly due to similarity in backgrounds, with no graduate student having more than 10 years of experience and most having fewer than three years' experience. Four students had witnessed accidents on site, and there appear to be some differences between these students' responses and those of the others, with for example more attention paid by these students to the identification of risks in scaffolding. However, this kind of analysis is difficult to validate given the small sample size.

Validity and limitations of the results

One tactic that researchers use when reporting results is to emphasise the utility of new technologies. The danger here, however, is of researchers imposing their assumptions onto the empirical material and generating false positives. Given the importance of safety in construction, the attempt here is to ground the discussion in the data collected. This involves a careful acknowledgement and discussion of the limitations of the evidence available.

Some limitations of the results arise from ambiguities in the model used. The CAD model had been simplified for scenario development and translation into the CAVE by the removal of some data and the addition of others. It contained a range of modelling errors and omissions. It is at times difficult to interpret where issues raised in the results are problems with the design, and where they are problems with the partial nature of the model. While the tactic had been to focus the research on the modelling and visualisation, and build strongly from the knowledge of experienced safety professionals, the lack of knowledge of the modeller affected the experiment in terms of issues arising around the examples of added temporary works. The 4D modelling that was used with both the graduate students and the safety professionals was of limited utility as it did not draw on a sufficiently detailed construction schedule.

In the experiments in which graduate students role-played designers and builders, they found it difficult to address issues only from their allocated roles, and so there was some discussion between the researcher and the participants. For example, where a 'builder' identified issues and the 'designer' was then asked to address them, the 'builder' emphasised: 'I am talking from a designer's perspective.' Participants also commented on lacking information on which to make a judgment. For example, when a researcher proposed: 'If I ask you to do some design change to make it safer, what measures can you think about?', the participant (acting as 'designer') replied: 'I should know the space and function of the space, but now I don't know the function of our space, so I can't make [a decision].' It is because of their limited nature that the data are not analysed in detail in this report.

5 Discussion and conclusions

All research, in contrast to many business operations, is a step into the unknown, in which negative or null results are as important a contribution to knowledge as positive outcomes. There are a number of issues that arose in this project that expose interesting issues with building safely by design, many of which are leading to new directions in further research.

First, the critical reading of the research literature on construction safety and design undertaken as part of this research suggests that the link between them is more subtle and problematic than earlier studies suggest. The causality of accidents on site is extremely complex, involving multiple factors: from momentary lapses of judgment, to the adequacy of training and the institutionalised practices of design and construction. Hence, the link between design and construction safety has often been assumed rather than articulated. This early work has helpfully championed and established the need for considering safety in the design stage of a project. In our work, however, we raise new questions about how researchers can study this link empirically, and to what extent safety professionals, graduate students and the researchers themselves can identify issues in a design model that might become safety concerns or issues on the construction site.

Second, the model used in the experiments did not provide enough context about the project. Both the safety professionals and graduate students asked the research team a wide number of questions about the model, and at times the researchers running the experiments improvised information, eg ‘Let’s say it was 4 metres’, or tried to direct attention to the parts of the model they felt were more relevant, eg ‘It should have some scaffolding, but we can ignore that’. This suggests the need to carefully build rich models that direct attention to relevant aspects and allow professionals to probe and discover further contextual information about the project, and to see it within the context of the site. The process animations used in this study were not sufficiently accurate to promote an understanding and identification of safe process solutions.

Third, the dialogue between graduate students is not directly comparable with that between the professionals because of differences in the media, scenarios and facilitation. However, it is striking how the professionals were able to mobilise their experience to focus on safety issues and draw attention to a wider range of possible solutions. For example, in a discussion about the crane, most student participants failed to recognise that this was fundamentally the wrong kind of crane and that a tower crane would be more appropriate. The students did not have the experience to hypothesise around different kinds of construction equipment, from cherry pickers to lifts and corner cranes; or the potential to develop safer methods through prefabrication of building components. These differences suggest a need for further work on the issues that are modelled and on the pedagogical methods that use models in teaching students about safety issues on construction sites. For example, an option here would have been for the research team to model a wider set of alternative types of equipment; to suggest a palette of options for prefabrication or building on the construction site; and the use of permanent or temporary solutions.

Below, we conclude with tentative recommendations and a reflection on the new trajectory of research on digital tools that support mindful practices, and the kinds of interaction that appear to be useful in their use. We then describe further research that seeks to extend this study and address some of its limitations.

Digital tools that support ‘mindful’ practices

The two different strands of research relevant to understanding the relationships between construction safety and digital design suggest very different approaches to the questions raised in this research. Taken separately, the first strand of literature shows there is a substantial body of research on the application of digital technologies to site safety issues, although very few tools for construction safety through design. The second strand of literature, based on empirical studies of safety-critical, digital and design practices, raises a concern about ‘mindlessness’ in the use of technologies. Yet what is exciting is that the juxtaposition of these two strands shows how the second strand has implications for research in the first.

This is particularly pertinent given the changing nature of practices. While much professional work has become mediated and distributed digitally, the making of buildings and infrastructure involves substantial and local physical labour. This work remains unchanged by the digital economy. The new digitally enabled processes change the distribution and nature of design practices and supply chains, altering the materials and information that are available on site. In any particular project, safe practices both draw on standardised regulations and tools, and are locally emergent.

The visualisation of rich models provides opportunities to facilitate innovative collaboration between designers and contractors at different moments and through different media. Yet the study suggests a need for researchers and model builders to test and refine the models with professional end-users, or to use models from the professionals' own projects to ensure that they can navigate them and that they provide a sufficiently accurate site-based model (perhaps with equipment and/or 4D modelling) before professional vision is turned to health and safety risks.

How the experienced professionals visualised health and safety concerns, in contrast to the students, suggests the potential of using virtual and CAVE technologies as a training or teaching tool. The professionals' style of structuring collaboration is in sharp contrast to the graduate student discussions, in which the researcher played a larger role in prompting and leading conversation. Rather than picking out isolated risks, the professionals' 'walk through' of the model captures a system of interrelations and complexity, and the implications of not integrating a risk or safety measure into the design. This contrast suggests directions for work on the pedagogical methods that use models in teaching students about safety issues on construction sites. Such further research might also explore how the interactions, which here are like the outcome from an on-site health and safety inspection, might become a more proactive, forward-planning and elimination exercise, to enable problems to be designed out of a project by knowledgeable individuals as the plan is produced.

Further research: design visualisation and site data

The research has been extended through collaboration with a major station project (project 2), which was initiated through meetings with an engineering design consultant in May 2011 and construction contractor D in July 2011.

This work examined how construction site professionals perceived and managed safety challenges associated with a building design.[90] The visualisation activity associated with this extended research involved site managers using the design model to reflect on and discuss safety issues that arose in the project with the site teams working on related ongoing projects.

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Appendix: Discussions of issues identified by the safety professionals

Voids on the middle floors

Professional 1: So pretty much every single void here is unprotected, isn't it?

Professional 2: Yep. Because what this does is gives you… I tell you what this does better than anything else, it gives you a sense of scale…

Professional 1: Yes.

Professional 2: … and, as we… talked about earlier, where we have a technique for managing voids like this, when we actually run the rebar through it, if it's too big a void then you can't do it. So if we went to that void over there, that would be impractical to run rebar through this. It just wouldn't work, it'd be too big a span. So getting the perspective of scale is actually quite important.

Professional 1: Don't know if this is relevant, but if this is going to be a void anyway in…

Professional 2: A permanent void…

Professional 1: … permanent void – you may wish to put up the permanent barrier or part of the permanent barrier, the effective part of the permanent barrier, as part of the construction right at the beginning. Right, as part of the construction process.

Professional 2: Yes.

Professional 1: Rather than having a temporary scaffold pole barrier, or whatever.

Professional 2: Yes. Because, of course, you could look at a drawing and say that…

Professional 1: Yes.

Professional 2: … any void smaller than that, then we run rebar through it. But, actually, when you go and stand in…

Professional 1: Yes.

Professional 2: … it – probably going to make a much more informed judgment from perspective.

Professional 1: Yeah, yeah.

Researcher: OK.

Professional 2: Of course we can't, can we jump down a floor?

Researcher: We can't go down, we can go up from here. It's just this floor and the top floor we want.

Professional 2: OK. So we can't get underneath the roof lights that you've got there?

Researcher: We can go above and see them from above.

Professional 2: But you can't go from below. Or can we see them a little bit just then? You can see them, but can't get directly underneath them.

Researcher: If you squat down you get a slightly better…

Professional 2: Oh, wow!

Staircase

Professional 2: Can we go to the staircase?

Professional 1: Yes. What did you pick up?

Professional 2: Well, what I didn't get was, if you look in here, you've got an area here which is…

Professional 1: Unprotected.

Professional 2: Well, why is that open? I couldn't see why that is.

Professional 1: So you'd close off half the void.

Professional 2: Yes. And it might be that there's a shaft going through there with, I don't know, a smoke extractor, or it might be a pressurised staircase, or something.

Professional 1: Yeah. No, I think that's a good point. As you say, there's absolutely no reason to have that as an open void because your access is just through there.

Professional 2: Or if there is a reason, then it actually identifies that you've got another edge protection issue that you've got to deal with before you get to this stage.

Professional 1: One thing I said about the staircases was why don't you put all the staircases just in slab form right from the beginning? At this stage of the construction, because you've got ladder access on the scaffolding, do you really need a ladder access? Why can't you just access throughout the building using the stairs, which are part of the permanent design?

Professional 2: Yes. I'll tell you what has just occurred to me with this though is… this must be a shaft of some sort. So let's say it's a pressurised staircase, and this is the extraction that corrects the negative pressure of whatever it is if you've got a fire. You could actually change the design where you bring those walls up with the structure, cast them as you come up.

Professional 1: Yeah, yeah, and they'll give you protection at the same time. That's a sequencing thing, isn't it? Good, OK.

Scaffolding and cladding

Professional 2: OK. Um, did you pick up on the scaffold?

Professional 1: Only there is no edge protection around it. What did you pick up then?

Professional 2: Well, I just asked the question: how do you tie it into the building?

Professional 1: Right.

Professional 2: Because obviously it's a large scaffold, got to be tied in. What is it?

Professional 1: Good point, an independent load.

Professional 2: So we can, how close can you get to that edge? OK, it's fallen off. So if you could pan round that way. Woo. You've got to find some way of tying this into the structure temporarily, but how's that going to be faced with getting your cladding on? Actually another point I've just noticed with that is – I presume there'll be some kind of bracketry to fix your cladding and the distance between the leading edge on the scaffold.

Professional 1: Yeah.

Professional 2: You need to set out so you can fit that all in.

Professional 1: Yes.

Professional 2: But at that point we've obviously got a gap.

Professional 1: A void.

Professional 2: Until the cladding goes on.

Professional 1: Yes. So you can see a clear void at the moment where things can just topple through…

Professional 1: You take on board my point about the ladder access up the scaffold? If you put in stairs right from the beginning, from internal, you could still have these scaffold lifts that you walk out onto, but actually access through the building going up the steps rather than…

Professional 1: I wouldn't have this if you've got your staircase in, then I wouldn't have this at all.

Professional 2: Exactly, yeah.

Professional 1: It could then be an access for putting the cladding on.

Professional 2: Yes, but even so, you'd probably get access, unless you needed half-lift access kind of thing. You could get access from each floor, you know, safely step out onto the scaffold. No, you probably couldn't because you're building up the building from outside.

Professional 1: I think, yeah, probably actually look at putting some kind of composite or something on the leading edge and put that as an independent access, well, work area access from the outside.

Crane

Professional 2: So the issue with the crane becomes very obvious now. If you're… saying this steel structure that, we're right, actually, here is, need a crane to lift it up, the lack of vision is very obvious.

Professional 1: Right. Yeah. Good point. So the person operating the crane can't see what he's doing.

Professional 2: And can we just look over this parapet wall here to the left? So that goes all the way down to ground floor. So there's no reason why you couldn't have, actually, put a tower crane up through the middle. Then you've got, potentially, a tower crane driver sitting about the project with a bird's eye view of it.

Professional 1: Yeah, go from inside. And not only that, you've probably got greater access to each part of the site than you would have on the perimeter.

Professional 2: Yeah, if you're talking about the corner crane which is meant to move about.

Professional 1: Yes.

Professional 2: Another thing we discussed was how you then ensure the integrity of the ground is working right.

Professional 1: Yes. Whereas if you've just got one stationary…

Professional 2: Yes, temporary works scheme. Well, you could even put it on tracks if you wanted to. But that's probably not necessary. In fact, you've got loads of scope to put up a tower crane or even two if you needed it. OK.

Roof

Professional 1: I don't know if you can prefabricate different bits of this roof, whether it's physically possible on the ground, then lift it up into position, rather than doing it in this more traditional way.

Professional 2: Yeah. On something this size…

Professional 1: It's difficult, isn't it?

Professional 2: No, I don't think it'd be difficult at all. On something this size, that's probably the best way to do it. You can almost fabricate this whole roof in one, possibly two pieces, then literally just crane lift it on.

Voids on roof and roof edge protection

Researcher: Some openings on the roof?

Professional 2: Yeah. If we go back to those openings that we looked at from below.

Researcher: These ones – where was it?

Professional 2: Well, they're similar to the ones below that we'd run rebar through that as a temporary arrangement. We don't know what those are for, whether it's services or roof lights.

Professional 1: Ah, so they're temporary openings – are they temporary openings?

Researcher: No.

Professional 2: No. Might be air-con units.

Professional 1: They're plant. So what [Professional 2] is saying is appropriate. You've got this relatively safe area in here where people can work safely, then you're asking them to come outside the safe area, the curtilage. Why is it outside and not within it? Is that what you're saying?

Professional 2: Well I was when I looked at it on the computer, but now looking at this, I suspect this is probably a louvered barrier which is part of the installation that's going into that area. I don't know.

Professional 1: Yes.

Professional 2: So it might actually be there for a function. A specific function for the equipment that is inside that area. So we don't know that, we need to understand it. But, what was obvious, if that could be moved over there then it would enclose that area so installation, maintenance, replacement etc, you've already got your protection of those.

[…]

Professional 2: So if the design is advanced enough you could manage out a lot of this, if that's what it's for.

[…]

Professional 2: What I was suggesting is that you get greater detail on the design, so that these voids may not need to be as big as they are.

Researcher: OK.

Professional 2: They could be split up into half a dozen small voids.

Professional 1: They may be oversizing them because they're not exactly sure of the detail.

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